J. ENVIRON. SYS., Vol. 3(2), Summer, 1973

Potential for Energy Conservation Through Increased Efficiency of Use[1]

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ABSTRACT

Opportunities exist for significantly increasing the efficiency with which energy is used in the United States. This paper discusses such opportunities for (a) the transportation sector (shifts from energy-intensive modes to energy-efficient modes, increased use of existing equipment, and technological changes to increase vehicle energy efficiency) and (b) the household sector (additional building insulation, electric heat pumps rather than electric-resistance heating, energy-efficient air conditioners, and addition of insulation to water heaters). Such energy efficiency improvements may require institutional and social changes, but technologies are generally available to implement such strategies. The benefits to the nation in terms of energy conservation, reduced reliance on energy imports and improved balance of payments, reduced adverse environmental impacts, lower dollar costs, and a return to a more conservative resource-use ethic are potentially large. Policies to achieve such goals would involve some life-style changes and important institutional decisions, but they do not imply a return to "caves and candles."

Introduction

Slowing energy growth rates by increasing efficiency of use is now being recognized as a potentially important contributor to resolution of United States energy problems. This paper explores a number of possibilities for increasing efficiency in the transportation and residential sectors. Opportunities exist for

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[1] Work reported here is sponsored by the National Science Foundation RANN Program under Union Carbide Corporation's contract with the U.S. Atomic Energy Commission.

(Testimony submitted to the U.S. Senate Committee on Interior and Insular Affairs pursuant to hearings on energy conservation, March 1973.)

doi: 10.2190/VQEU-MHQE-T0ED-FNJC
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Table 1. End Uses of Energy in the United States, 1970*

Industry	
Process steam	16%
Direct heat	11
Electric drive	8
Raw materials	6
Electrolytic processes	1
Transportation	
Intercity passengers	6
Urban passengers	9
Intercity freight	4
Urban freight, other	6
Residential/Commercial	
Space heating	18
Water heating	4
Air conditioning	3
Refrigeration	2
Other	6

* Total energy use was 67,400 trillion Btu in 1970.

significantly reducing energy growth rates through efficiency improvements in these areas.

During the past two decades, United States energy use has grown at an average annual rate [1] of 3.5%—more than double the population growth rate. Industry (manufacturing, mining, agriculture) accounts for about 40% of the energy budget, transportation of freight and passengers for 25%, homes for 20%, and commerce for the remaining 15% [1, 2].

Table 1 shows the major end-uses [2] of energy for 1970. Transportation is the largest. Space heating of homes and commercial establishments is the second largest use, consuming 18%. Industrial energy uses (process steam, direct heat, electric drive, fuels used as raw materials, electrolytic processes) account for 42%. The other 15% is used in the commercial and residential sectors for water heating, air conditioning, refrigeration, cooking, lighting, and operating small appliances.

Transportation

In 1970 transportation of people and freight consumed [1] 16,500 trillion Btu. Increases in transportation energy use are due to growth in traffic levels, shifts toward the use of less energy-efficient transport modes, and declines in energy efficiency for individual modes [3].

FREIGHT TRAFFIC

Intercity (IC) freight is moved by various modes, including railroad, truck, waterway, pipeline, and airplane. Figure 1 shows the energy-intensiveness (EI) for each of these modes [3]. EI is the inverse of energy efficiency; the more energy-intensive a mode, the less efficient it is. Pipelines and waterways are the most efficient modes; however, they are limited in the kinds of materials they can transport and in the flexibility of their pickup and delivery points. Railroads are slightly less efficient than pipelines and waterways. Trucks, faster and more

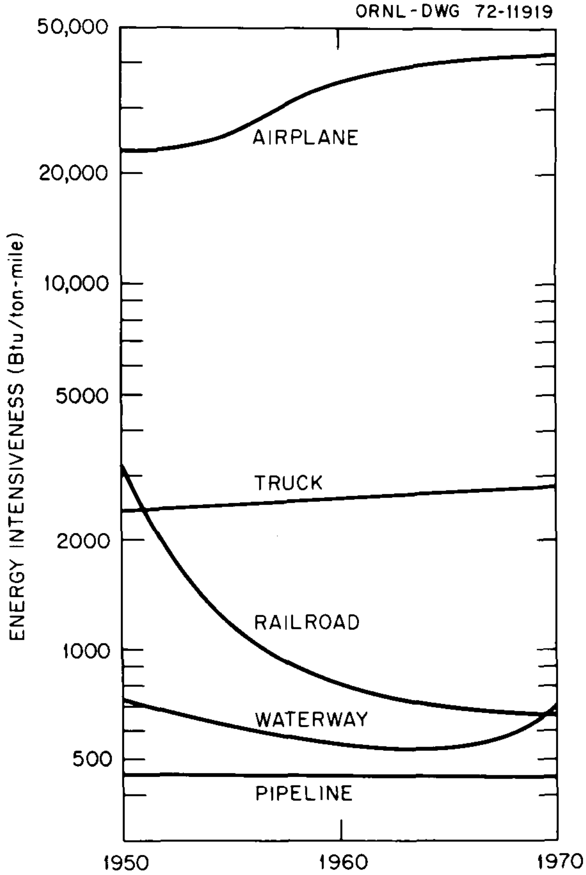

Figure 1. Historical variation in energy-intensiveness of intercity freight modes.

Table 2. Historical Energy Consumption Patterns for Transportation

Year	Total traffic	Per cent of Total Traffic						Total energy (10^{12} Btu)	Average EI
		Air	*Truck*	*Rail*	*Waterway and pipeline*	*Auto*	*Bus*[a]		
		Intercity Freight Traffic							
1950	1350[b]	0.02	13	47	41	–	–	2700	2000[d]
1960	1600	0.05	18	38	44	–	–	1800	1100
1970	2210	0.15	19	35	46	–	–	2400	1100
		Intercity Passenger Traffic							
1950	500[c]	2	–	7	–	86	5	1700	3400[e]
1960	800	4	–	3	–	91	2	2700	3400
1970	1120	10	–	1	–	87	2	4300	3800
		Urban Passenger Traffic							
1950	310[c]	–	–	–	–	85	15	2100	7000[e]
1960	430	–	–	–	–	94	6	3300	7700
1970	710	–	–	–	–	97	3	5700	8000

[a] Intercity bus or urban mass transit.
[b] Billion ton-miles.
[c] Billion passenger-miles.
[d] Btu/ton-mile.
[e] Btu/passenger-mile.

flexible than the preceding modes, are only one-fourth as efficient as railroads. Airplanes, the fastest mode, are only one-sixtieth as efficient as trains.

After World War II, EI for railroads decreased sharply because of the shift from coal-burning steam locomotives to diesel locomotives. On the other hand, EI for airplanes increased dramatically, as airlines traded energy for speed.

Between 1950 and 1970 the percentage of freight traffic carried by rail declined steadily (Table 2), offset by increases in truck, pipeline, and airplane traffic. During this period, energy consumption for IC freight traffic fell by 12% in spite of a 64% increase in total traffic. Overall EI declined by 46% because EI for trains decreased by about 80%. Were it not for this sharp drop in railroad EI, overall freight EI would have increased as freight traffic shifted to modes with higher (and growing) EI's.

PASSENGER TRAFFIC

IC passenger traffic is carried primarily by automobile and, to a lesser extent, by airplane, bus, and train. Figure 2 shows EI for each of these modes [3]. The variation in EI is considerable, but not as large as for freight transport. Buses and trains are the most efficient modes, followed by autos and airplanes. In 1970 EI for airplanes was five times higher than for buses. However, airplanes are the fastest mode, and automobiles are the most convenient in terms of schedules and routes.

Between 1950 and 1970 the fraction of IC passenger traffic carried by airplane climbed rapidly at the expense of trains and buses (Table 2). Energy consumption increased by 155% as a result of a 125% increase in traffic and a 14% increase in overall EI. This increase in EI was due to increases in EI for individual modes and the shift from buses and trains to airplanes.

Urban passenger traffic is carried almost exclusively by car, with only a small and declining fraction carried by mass transit (buses and electric transit). As Fig. 2 shows, mass transit is more than twice as energy-efficient as are autos [3]. Urban EI values are more than double comparable IC values because of poorer vehicle performance (fewer miles/gallon) and poorer utilization (fewer passengers/vehicle) in cities.

Between 1950 and 1970 the fraction of urban passenger traffic carried by cars increased steadily (Table 2). Energy use increased by 165%, caused by a 132% increase in traffic and a 14% increase in EI. Increased EI was due to increased individual modal EI and the shift from mass transit to automobiles.

The factors accounting for transportation energy growth [3] during the 1960s are shown in Fig. 3. Growth in per-capita transportation (especially passenger travel) accounted for more than half the decade's energy growth. Population growth accounted for one-fourth of the rise, and increased EI for one-fifth. Thus, transportation energy growth is due primarily to rising traffic levels and secondarily to shifts toward high-EI modes and increases in EI for individual modes.

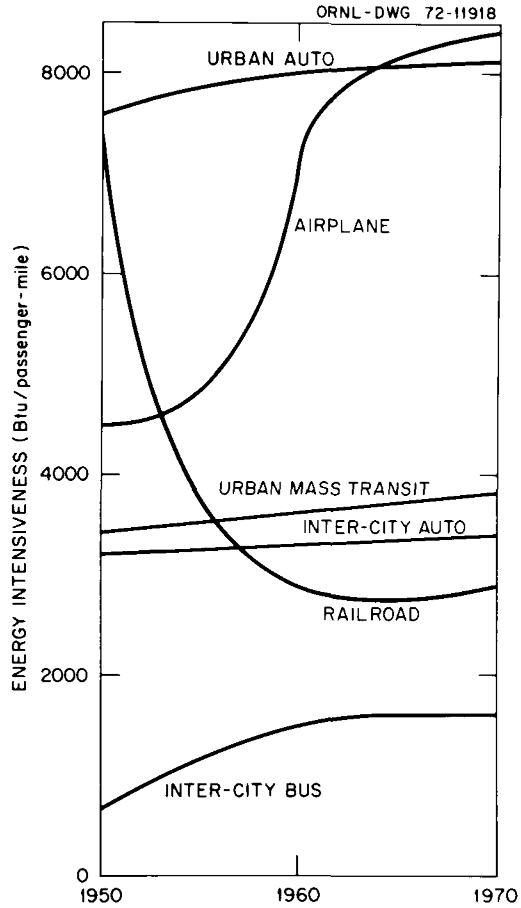

Figure 2. Historical variation in energy-intensiveness of passenger modes.

IMPROVING ENERGY EFFICIENCY

Transportation energy growth can be slowed in a number of ways. One way is to shift traffic [4, 5] from energy-intensive modes to energy-efficient modes (Figs. 1 and 2). In general, such shifts require no new technologies; however, they may involve life-style changes (walking or riding the bus in cities rather than driving) and major institutional actions (massive funding to revitalize mass transit systems). Table 3 illustrates potential energy savings for a shift of one billion passenger-miles (or ton-miles) from one mode to another (although historical trends have been in the opposite direction).

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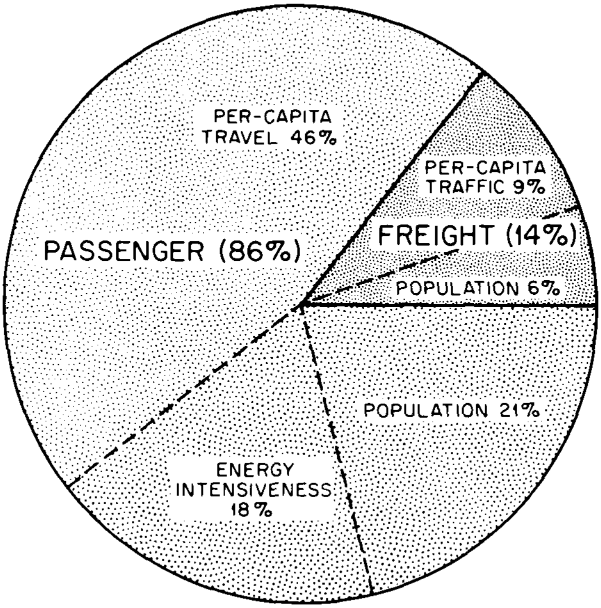

Figure 3. Factors accounting for the increase in transportation energy use between 1960 and 1970.

Transport EI can also be lowered by using existing equipment more fully, i.e., increasing the fraction of capacity utilized. Urban autos, mass transit, and trains have particularly low load factors. Table 3 shows potential energy savings per billion passenger-miles for a 10-percentage point increase in load factor for these modes. Achieving such load factor improvements requires no new technologies; however, life-style changes associated with increased car-pools, consolidation of auto trips, and greater use of mass transit and trains with existing routes and schedules would be needed.

Finally, application of existing and emerging technologies can increase vehicle energy efficiency and also improve transport system comfort, speed, and service. These latter improvements might help to increase system load factors and induce a shift to energy-efficient modes. Automobiles offer large potential improvements. For example, a 2200-pound auto (e.g., Vega or Pinto) with radial tires, standard transmission, and no air conditioner will consume less than half as much fuel per mile as a typical full-size auto (e.g., Impala or Galaxie) [6]. Table 3 shows the energy savings possible (per billion passenger-miles) for 33% reductions in EI for autos, airplanes, and trains. While such EI reductions are technologically possible, [6, 7] other technologies, such as the supersonic

Table 3. Transportation Energy Conservation Strategies

From 1970 situation	*To energy-efficient alternative*	*Energy savings[a] 10^{12} Btu*
	Passenger traffic: modal shifts	
Intercity auto	Intercity bus	1.8
Airplane	Intercity bus	6.8
Urban auto	Mass transit	4.3
	Passenger traffic: load factor increases[b]	
Urban auto (28%)	Urban auto (38%)	2.1
Mass transit (20%)	Mass transit (30%)	1.3
Intercity train (37%)	Intercity train (47%)	0.6
	Passenger traffic: technological changes[c]	
Intercity auto (3400)	Intercity auto (2300)	1.1
Urban auto (8100)	Urban auto (5400)	2.7
Airplane (8400)	Airplane (5600)	2.8
Train (2900)	Train (1900)	1.0
	Freight traffic: modal shifts	
Truck	Train	2.1
Airplane	Train	41.3

[a] Energy savings are computed on the basis of a one billion passenger-mile (or ton-mile) effect, about 0.05% of 1970 passenger traffic (or intercity freight traffic).

[b] Energy savings given are for a 10 percentage point increase in load factor; numbers in parentheses are load factors.

[c] Energy savings given are for a 33% reduction in vehicle EI; numbers given in parentheses are EI values in Btu/passenger-mile.

transport, V/STOL aircraft, high-speed trains, and air-conditioned autos, would increase transport EI.

A SCENARIO

Using the information in Table 3, one can devise various energy consumption scenarios for transportation. The following fanciful scenario for 1970 reduces transportation energy use by 50% with no reduction in total travel:

> Half the intercity freight carried by truck and by air is shifted to rail with no load factor or technological changes.
>
> Half the intercity passenger traffic carried by air and one-third the traffic carried by car is shifted to bus and train. Railroad load factor is increased 10 percentage points, and technological improvements in autos, trains, and airplanes (Table 3) are incorporated.

Half the urban auto traffic is shifted to mass transit. Both mass transit and urban auto load factors are increased 10 points. Urban auto design is changed (Table 3).

The purpose of this unrealistic scenario is to show that significant reductions in transportation EI are not impossible. The time-scale for such changes, however, is probably a decade or two. Whether or not we improve system efficiency depends more on our collective will and judgment than on scientific and technological breakthroughs.

Households

In 1970 Americans consumed 13,400 trillion Btu in their homes [1, 2]. More than half this energy was used for space heating, about 15% for water heating, and 4% for air conditioning. (Air conditioning is the fastest growing residential energy user with an annual growth rate of about 15%.) The remainder was used for cooking, refrigeration, lighting, and operating small appliances.

SPACE HEATING

The nearest approach to a national standard for thermal insulation in residential construction is "Minimum Property Standards (MPS) for One and Two Living Units," issued by the Federal Housing Administration (FHA) [8]. In June, 1971, FHA revised the MPS to require more insulation, with the stated objectives of reducing air pollution and fuel consumption. A recent study [8] estimated the value of different amounts of thermal insulation in terms both of dollar savings to the homeowner and of reduction in energy consumption. Hypothetical 1800-ft^2 model homes were placed in three climatic regions (represented by Minneapolis, New York, and Atlanta), each representing one-third of the United States population.

Table 4 shows the energy savings achieved in both heating and air conditioning through increased levels of insulation. The "economic optimum" level of insulation is that amount of insulation which yields the maximum economic benefit to the homeowner (based on 1970-71 fuel prices). The 1971 revised MPS provide appreciable energy and dollar savings for residential heating, although more insulation is needed to minimize the long-term cost to the homeowner.

Total U.S. energy use in 1970 was 67,400 trillion Btu, about 11% of which was used for residential space heating and 7% for commercial space heating [1, 2]. Table 4 shows nationwide average reductions in energy required for space heating of 43% for gas homes and 41% for electric homes in going from the 1965 MPS to the economic optimum insulation [8]. An average savings of 42%, applied to all residential units (single-family and apartment, gas and electric), would have amounted to 3,100 trillion Btu in 1970 (4.6% of total energy consumption). These energy savings are somewhat understated: as

Table 4. Comparison of Residential Heating and Cooling Requirements by Region by Insulation Level

	Region			
	Atlanta	*New York*	*Minneapolis*	*U.S. average*[a]
	Space Heating			
Annual heat loss with 1965-MPS standards (million Btu/home)				
Gas	73.5	134	171	126
Electricity	73.5	119	138	110
Heat pump COP[b]	2.20	2.02	1.61	1.82
% reduction in heat loss between 1965- and 1971-MPS standards				
Gas	16	29	35	29
Electricity	16	20	20	19
% reduction in heat loss between 1965-MPS standards and economic optimum				
Gas	31	49	43	43
Electricity	53	47	29	41
	Air Conditioning			
Annual heat gain with 1965-MPS standards (million Btu/home)				
Gas	23.6	11.0	10.5	15.0
Electricity	23.6	9.87	9.91	14.5
% reduction in heat gain between 1965- *and 1971-MPS standards*				
Gas	0	10	11	5
Electricity	0	0	6	1
% reduction in heat gain between 1965-MPS standards and economic optimum				
Gas	7	26	18	14
Electricity	18	18	13	17

[a] U.S. averages are computed assuming that the population is divided equally among the three regions represented by Atlanta, New York, and Minneapolis.

[b] COP is Coefficient of Performance (ratio of heat delivered by heat pump to energy input).

insulation is added, the heat from lights and appliances becomes a significant part of the total heat required.

The end-use efficiency of gas- or oil-burning home heating systems is about 60% (claimed values range from 40 to 80%), meaning that 1.7 units of heat must be extracted from the fuel for each unit delivered to the living area of the home.

Electrical resistance heating is more wasteful of primary energy than is direct combustion heating. The average efficiency for electric power plants [1] in the United States is about 33%, and the efficiency of transmitting and distributing the power to the customer is about 91%. The end-use efficiency of resistance heating is 100%; so, the overall efficiency is 30%. Thus, for every unit of heat delivered in the home, 3.3 units of heat must be extracted from the fuel at the power plant. Therefore, the resistance-heated home requires twice as much fuel per unit of heat as the gas- or oil-heated home, assuming equivalent insulation.

Electric heat pumps provide thermal energy for space heating that is appreciably greater than the thermal equivalent of the input electric energy, making them roughly comparable to gas- or oil-fired systems from a fuel-use standpoint [9]. Heat pumps extract energy from the cold outside air, boost the temperature of this energy, and deliver it along with the thermal equivalent of the input electric energy, to the inside air.

Both the input power requirement and the output thermal energy of a heat pump vary as functions of outside air temperature, necessitating the use of temperature-duration information in evaluating the seasonal performance of the system. The performance of a heat pump in the hypothetical home described in the insulation study [8], optimally insulated for electric heat and air conditioning, was examined for the same climatic regions. The results (Table 4) show that, even in the Minneapolis region, the heat pump significantly reduces electricity use for space heating. If equal populations using electric heat are assumed for the three regions, universal adoption of heat pumps would reduce electricity consumption for space heating by 45% (a 32 billion kWhr saving for 1970) [9].

From the homeowner's economic standpoint, the energy savings achievable by using the heat pump instead of resistance heating must be balanced against higher capital and maintenance costs. These costs have tended to retard widespread use of heat pumps; in 1970 only 11% of electrically heated households in the U.S. had heat pumps [10]. Hopefully, recent efforts by manufacturers to improve reliability of the units may increase their acceptability.

AIR CONDITIONING

In all-electric homes, air conditioning ranks third as a major energy-consuming function, behind space and water heating. Air conditioning is particularly important because it contributes to or is the cause of the annual peak load that occurs in the summertime for many utility systems.

In addition to reducing the energy required for space heating, ample use of insulation reduces the energy required for air conditioning (Table 4). Use of the economically optimum amount of insulation would result in a nationwide average reduction of electricity consumed for air conditioning of 14% for gas homes and 17% for electric homes, compared to 1965-MPS compliance homes [8].

The popularity of room air conditioners is evidenced by an exponential sales growth [9] with a doubling time of 5 years over the past decade; almost 6 million were sold in 1970. The strong growth in sales is expected to continue since industry statistics show a market saturation of only about 40%.

There are about 1200 models of room air conditioners available on the market today, sold under 50 different brand names [11]. A characteristic of the machines that varies widely but is not normally advertised is the efficiency with which energy is converted to cooling. Efficiency ranges from 4.7 to 12.2 Btu/watt-hr. Thus, the least efficient machine consumes 2.6 times as much electricity per unit of cooling as the most efficient one. Figure 4 shows the efficiencies of all units having ratings up to 24,000 Btu/hr, as listed in Ref. 11. The highest efficiencies are available in the larger 115-volt models, not because of technological advantages at the lower voltage but because of the marketing advantage of a unit having a relatively large rating that is operable on existing electric circuits in the home.

The matter of whether it is to the consumer's monetary advantage to purchase high-efficiency models, possibly at higher initial cost, is difficult to resolve. The choice should be the model providing the lowest total purchase plus operating cost over the lifetime of the unit. Expected annual hours of operation and the unit cost of power vary appreciably for different sections of the country. In addition, the selling price of a room air conditioner is influenced by many factors other than efficiency (i.e., trim features, fan speeds, ventilation and exhaust features), obscuring the effect of efficiency on price. As an example [9], one manufacturer markets eight models rated at 6000 Btu/hr with the following efficiencies and suggested retail prices:

Unit	*Efficiency (Btu/watt-hr)*	*Price ($)*
1	4.9	200
2	6.1	160
3	6.1	170
4	6.1	180
5	6.7	210
6	6.9	170
7	6.9	180
8	6.9	190

Efficiency can be improved by increasing the surface areas of the condenser and evaporator coils, by increasing the air flow through these coils, and by reducing the mechanical and fluid friction losses in the compressor. Improved compressor performance is often obtained with a 4-pole, 1800 rpm compressor instead of a 2-pole, 3600-rpm one.

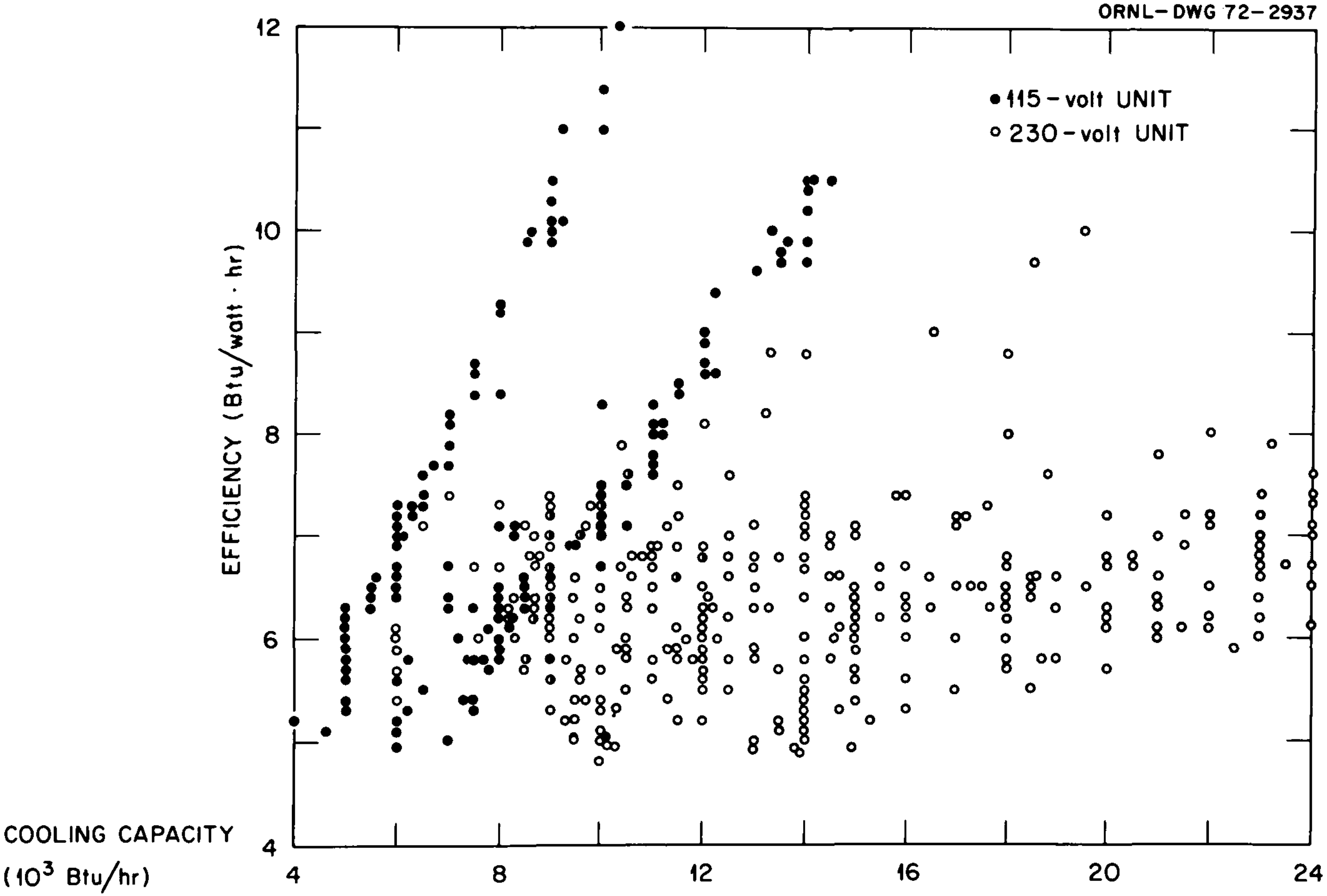

Figure 4. Efficiencies of 1972 model room air conditioners.

An improvement in average efficiency of room air conditioners would result in appreciable reductions in the nation's electricity consumption and required generating capacity [12]. If it is assumed that the size distribution of all existing room units is that for the 1970 sales, the average efficiency is 6 Btu/Whr, and the average annual operating time is 886 hr/year, then the nation's room air conditioners consumed 39.4 billion kWhr during 1970, with a connected load of 44,500 MW. If the assumed efficiency is changed to 10 Btu/Whr (a value well below the highest efficiencies available today), the annual power consumption would have been 23.6 billion kWhr, a reduction of 15.8 billion kWhr, equivalent to a reduction in coal strip-mining of 1500 acres for 1970. The connected load would have decreased to 26,700 MW, a reduction of 17,800 MW. These reductions would have occurred in the summer, when many utility systems experience their annual peak loads and are hard pressed to meet the demand on their systems.

WATER HEATING

With the exception of space heating, water heating consumes more energy than any other single function in the home. An electric water heater consumes about 4500 kWhr/year.

The energy consumed for water heating [13] may be separated into three components: that required to heat water that is actually used as hot water; that required to heat water that cools off in hot water piping between uses; and that required to make up heat losses from the water heater to its surroundings. The first component can be reduced by measures to conserve hot water, both conscious efforts on the part of the consumer and more efficient laundry and dishwashing equipment, or by use of waste heat to preheat incoming cold water. The second component can be reduced by shortening the length of hot water piping, through consolidation of hot water use points or multiple water heaters (this may increase the third component), or by insulating the hot water piping. The third component can be reduced by the use of more or better insulation for the water heater and by insistence that a thermal trap be installed in the hot water line leaving the heater.

We investigated these possibilities for energy conservation [13]: preheating incoming cold water during summer months by a heat exchanger installed in the attic; insulation of hot water piping; and additional insulation for the water heater. In each case, the capital cost of the improvement was estimated and compared with the capitalized value of the resulting annual electricity saving. Although the study assumed the improvements to be for a new home, an existing home could be retrofitted with them at little additional cost.

Attic preheaters and insulation of hot water piping each saved some energy, 150 to 200 kWhr/year, but not enough to recover their initial costs through reduced power bills (at present electricity prices). Use of additional insulation on the water heater itself, however, appears promising.

In the study a 50-gallon water heater, assumed to be in a space where the temperature fluctuates with the seasons between 55 and 75°F, has an annual heat loss of 960 kWhr, or about 20% of the total energy use, with the factory-installed 2-inch thick insulation. The initial cost, resultant annual energy savings, and net monetary savings for additional insulation are given in Table 5 for several electricity prices. Monetary savings are power cost savings less the annual equivalent of the incremental initial cost.

Table 5. Benefit of Additional Insulation for Electric Water Heaters

Thickness (inches)	*Cost ($)*	*Energy saving (kWhr/yr)*	*Net monetary saving ($/yr)* at power cost (cents/kWhr) of*		
			2	*3*	*4*
1	3.96	188	3.20	5.08	6.96
2	8.34	290	4.61	7.51	10.41
3	13.33	350	5.10	8.60	12.10
4	18.93	384	4.98	8.82	12.66

* Net monetary saving is annual power cost saving less annual equivalent of additional initial cost (7% interest, 10-yr life).

At the 1971 national average residential electricity price of 2.2c per kWhr, three inches of extra insulation is justified. If each of the 16.1 million electric water heaters in use in 1970 had three additional inches of insulation, the nation's electricity consumption for water heating would have been lower by 5.6 billion kWhr, or by the usual output of one 1000 MW power plant, that year. Adding insulation to gas water heaters is likely to provide similar energy and dollar savings. Electric water heaters have a normal service life of about 10 years. As a result, the effect of improved insulation standards would be reflected by lower electricity consumption in a relatively short time.

Conclusions

We discussed several end-uses of energy for which greater efficiency is feasible: transportation, space heating, air conditioning, water heating. Shifts to less energy-intensive transport modes, increases in system load factors, and technological improvements in engine and vehicle design would reduce transportation energy use.

Adding building insulation to homes would reduce both space heating and air conditioning energy requirements and save money for homeowners. The use of heat pumps, rather than electric-resistance heating, would also save energy, as would increased use of efficient air conditioners. Finally, adding insulation to water heaters would save both energy and money.

Energy-efficiency improvements can be effected for other end-uses besides those considered here. Such potential savings [12] include increased recycle of energy-intensive materials such as metals [14], reduced packaging of consumer goods, use of waste heat from power plants for industrial and space heating purposes [15], closer attention to commercial lighting, and use of total energy systems to provide both heat and electricity for commercial operations.

Recent history shows a steady growth in energy use. However, a number of emerging factors (fuel shortages, rising fuel prices, land-use questions, environmental concerns) could reverse these historical trends. It is technologically feasible to slow energy growth by increasing efficiency of use. Implementing such efficiency improvements will depend primarily on institutional actions and on individual decisions.

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